GSFC · 2015

Multiple Loop Heat Pipe Radiator for Variable Heat Rejection in Future Spacecraft

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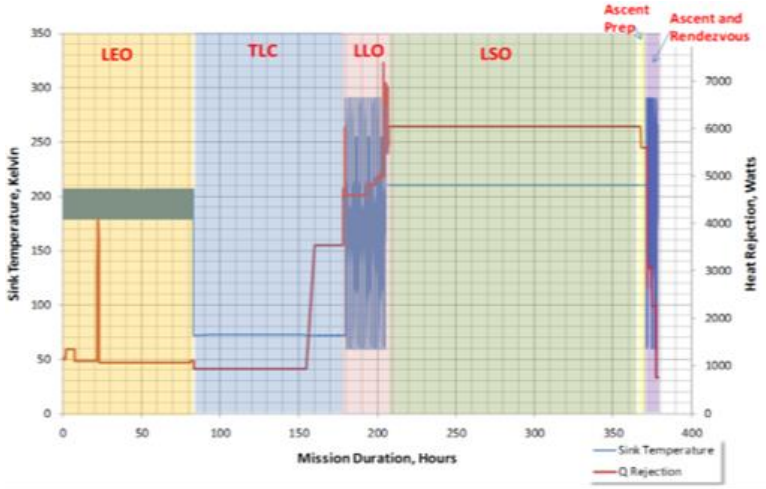
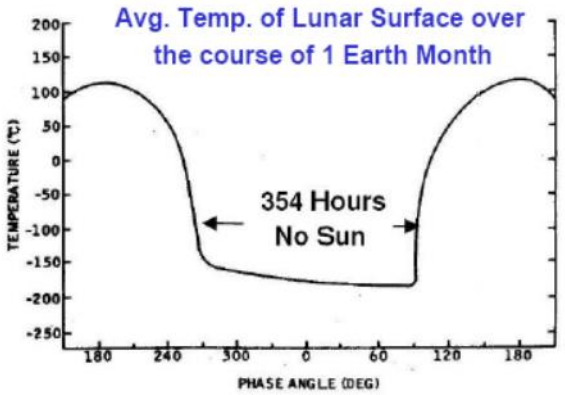
Motivation

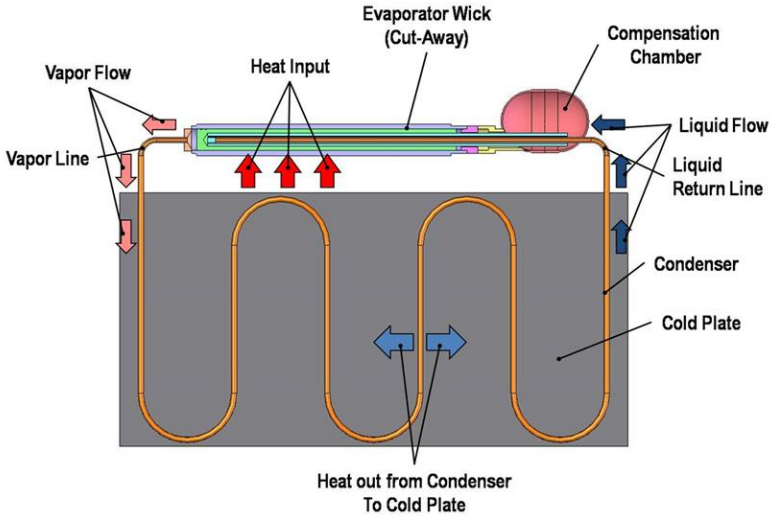
- Challenging space thermal environments with varying heat loads and sink temperatures will require spacecraft thermal management systems to have variable heat rejection with high turndown
  - Future manned spacecraft
  - Future Lunar and Martian rovers
- **Loop heat pipes (LHPs)** have been successfully used for variable heat rejection on spacecraft. Heat transfer with LHPs can be actively controlled through compensation chamber (CC) heating. However…
  - Heat loads practically limited to <1 kW
  - Power requirements for CC heating results in large mass penalties

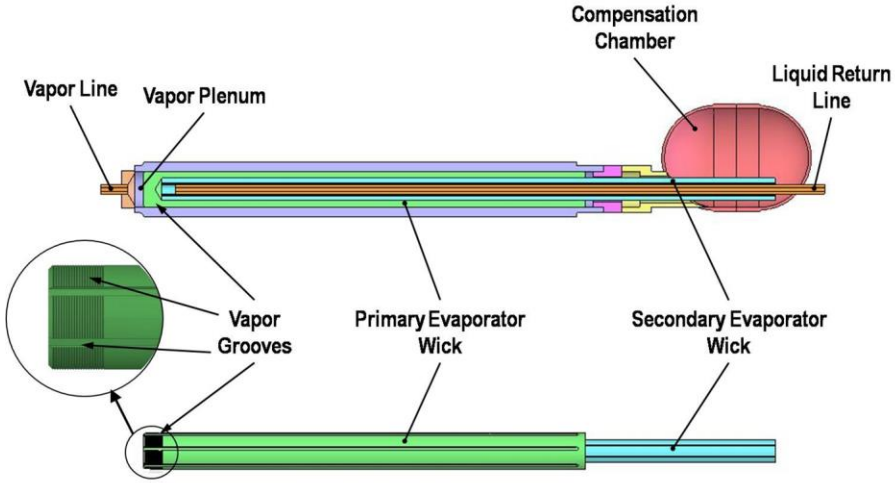




Loop heat pipe operation

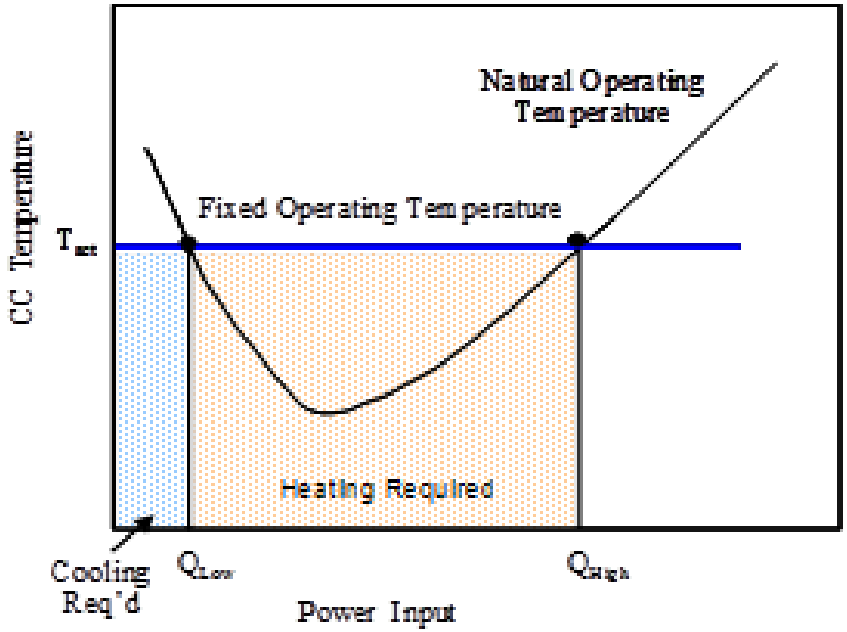
- Heat is applied to outside of **primary wick,** which is saturated with liquid
- Vapor is generated which travels through **vapor line** to **condenser**
- Vapor is condensed and the liquid sub-cooled in the condenser
- Cold liquid returns to the **compensation chamber (CC)** through **liquid line**
- CC contains saturated two-phase mixture of liquid and vapor
- CC is a lower temperature and pressure than vapor side of primary wick
- The **secondary wick** regulates liquid and vapor communication between CC and primary wick





Loop heat pipe control

- LHP evaporator operating temperature is governed by the saturation temperature in the CC
- CC saturation temperature varies with heat load and sink temperature
- Typical LHP temperature control for spacecraft is to cold bias the CC and use electrical heaters
- For a given sink temperature:



"Loop Heat Pipe Startup Behaviors", Jentung Ku, 18th Workshop on Thermophysics in Microgravity, El Segundo, CA, March 24, 2014.

- Other methods of LHP temperature control:
  - Aluminum coupling blocks or heat exchanger between vapor and liquid lines
  - Thermoelectric devices
  - Thermal control valves for vapor bypass
  - VCHPs between evaporator and liquid line

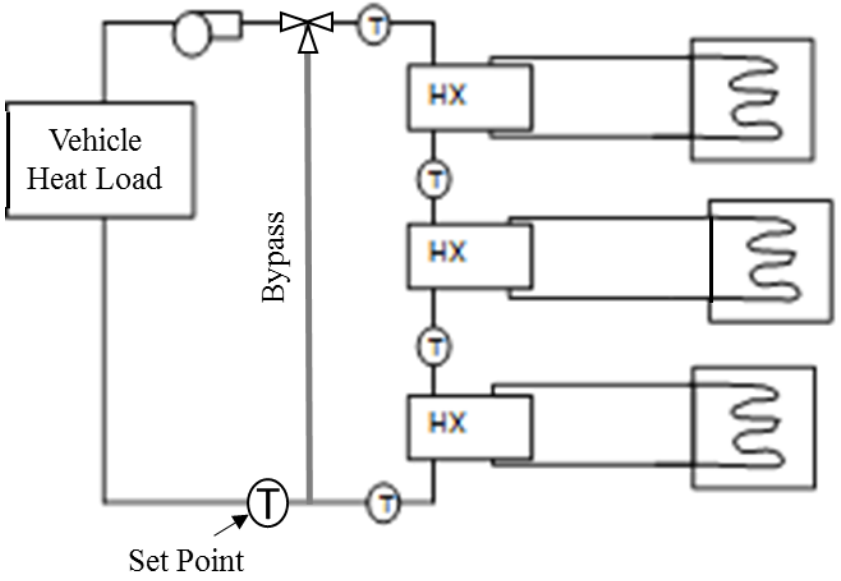
Multiple LHP system concept

Multiple LHP Variable Heat Rejection System

- ACT has developed a multiple-LHP system concept for rejecting large variable heat loads (several kW) from an intermediate single-phase pumped loop that removes heat from the crew compartment of a manned spacecraft
- Goal is to maintain the set point temperature of the single phase fluid returning to the vehicle as the heat load and sink temperature changes

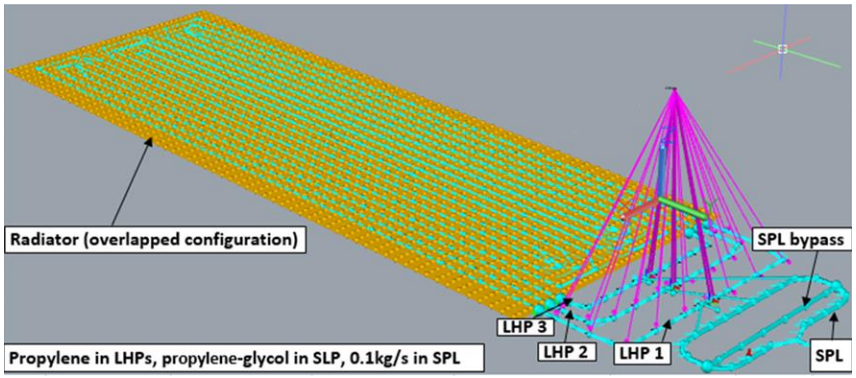
- **Key components of concept:**

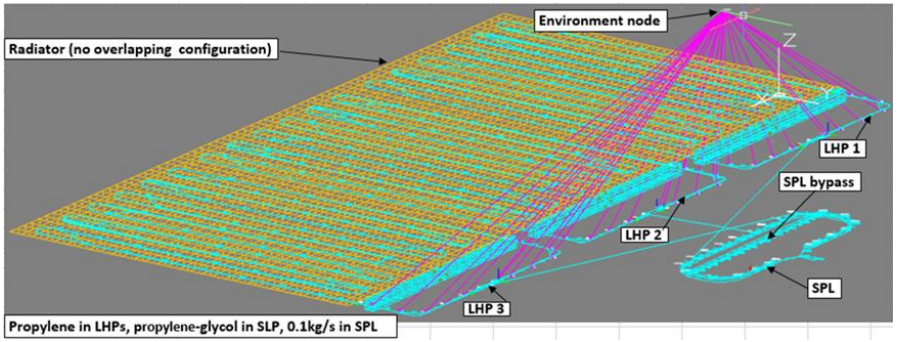
- LHP evaporators coupled to loop in series
- Valve and bypass loop in single-phase loop, such that local flow rate passing through heat exchangers with LHP evaporators can be modulated
- Changing local flow rate changes fluid temperature drop across heat exchangers, thus changing LHP evaporator temperatures, thus changing overall thermal resistance of LHP



Thermal Desktop modeling

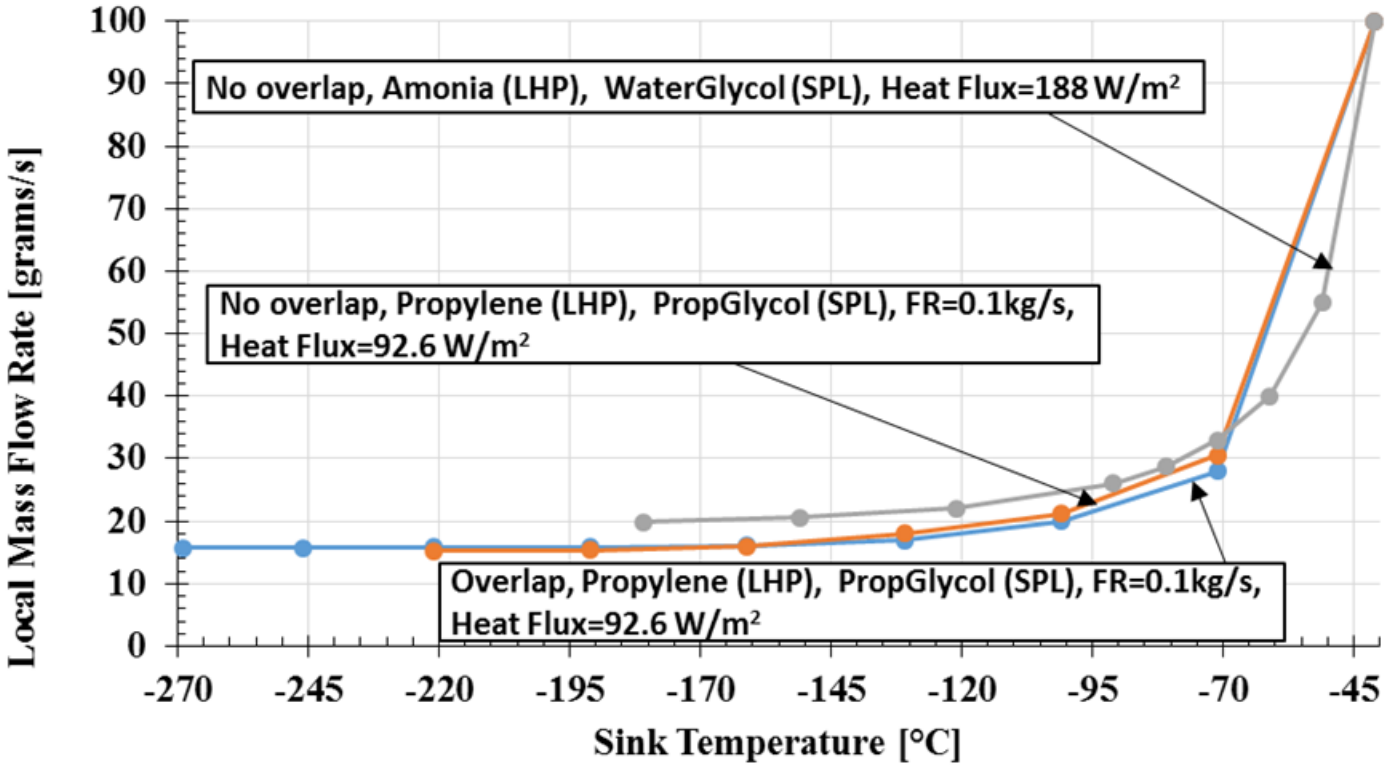
- A systematic numerical evaluation of this concept was performed using Thermal Desktop
- Single phase fluid properties:
  - 50/50 propylene-gycol/water
  - 0.1 kg/s total mass flow rate
  - Set point temperature of 8°C
- Three LHPs, sized to reject 2500 W in warmest sink (-41°C)
  - Propylene working fluid
- Two configurations examined:
  - Separate radiator panels for each LHP
  - LHPs share common radiator panel, with overlapping condenser lines





Thermal Desktop modeling

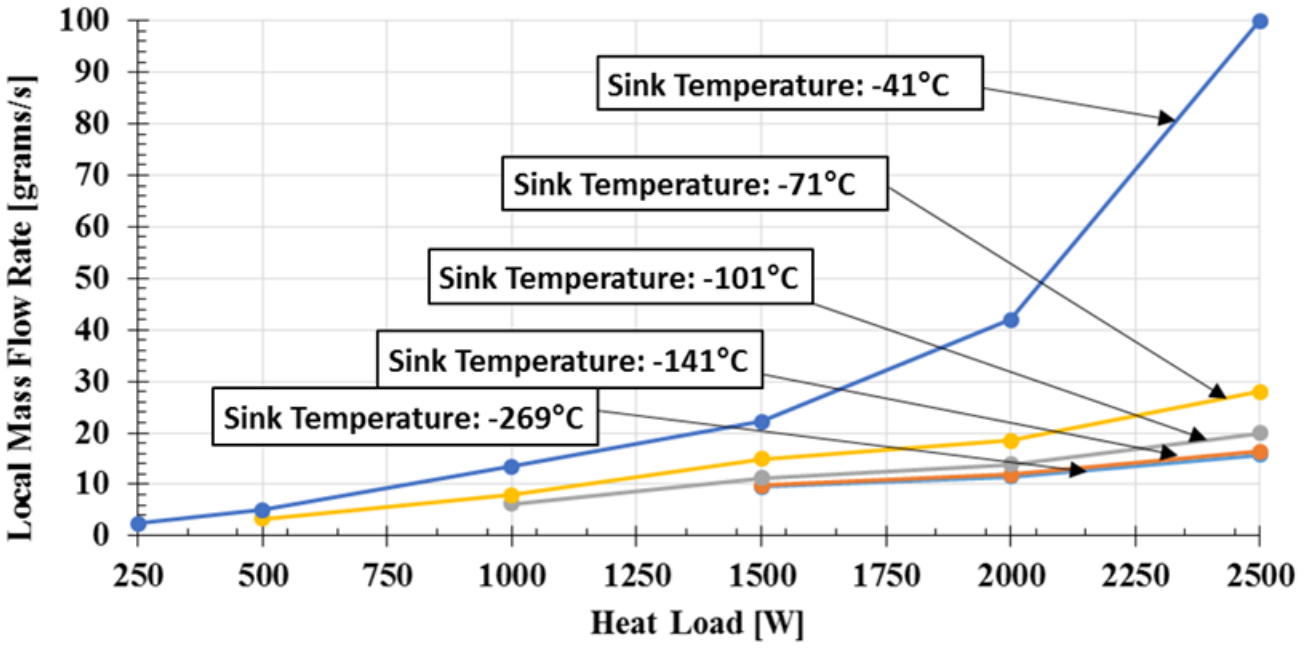
Constant power (2500W) **into** ***variable sink temperature***



Local Mass flow rate required to maintain set point temperature while sink temperature changes for constant power (2500W)

Thermal Desktop modeling

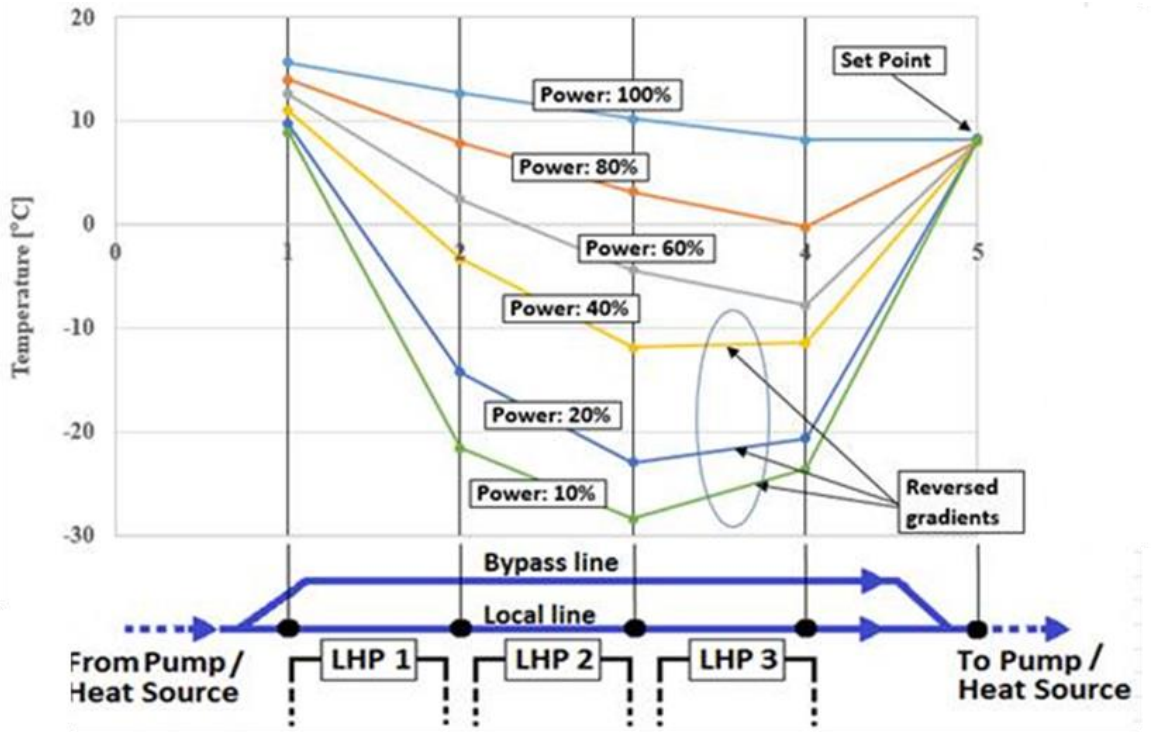
Variable power into *constant sink temperature*



Local Mass flow rate required to maintain set point temperature while power changes (performed for various sink temperatures) - Results for 3 LHP with non-overlapping condenser lines

Thermal Desktop modeling

Variable power into *constant sink temperature*

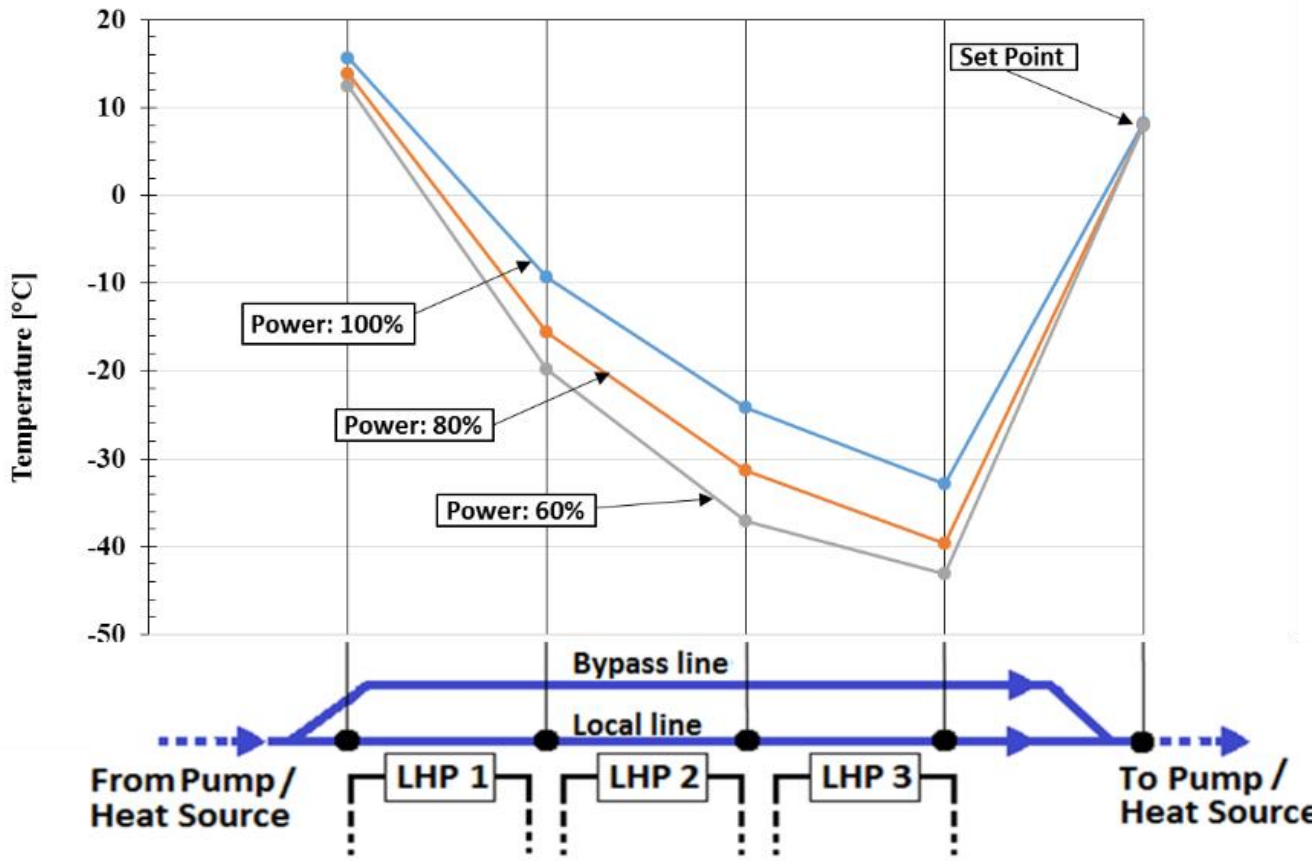


Temperature distribution along the local portion of the SPL as power changes for a sink temperature of -41°C

- In the cases where there is a reversed temperature gradient, the third LHP is completely shut down and loop is gaining heat from environment

Thermal Desktop modeling

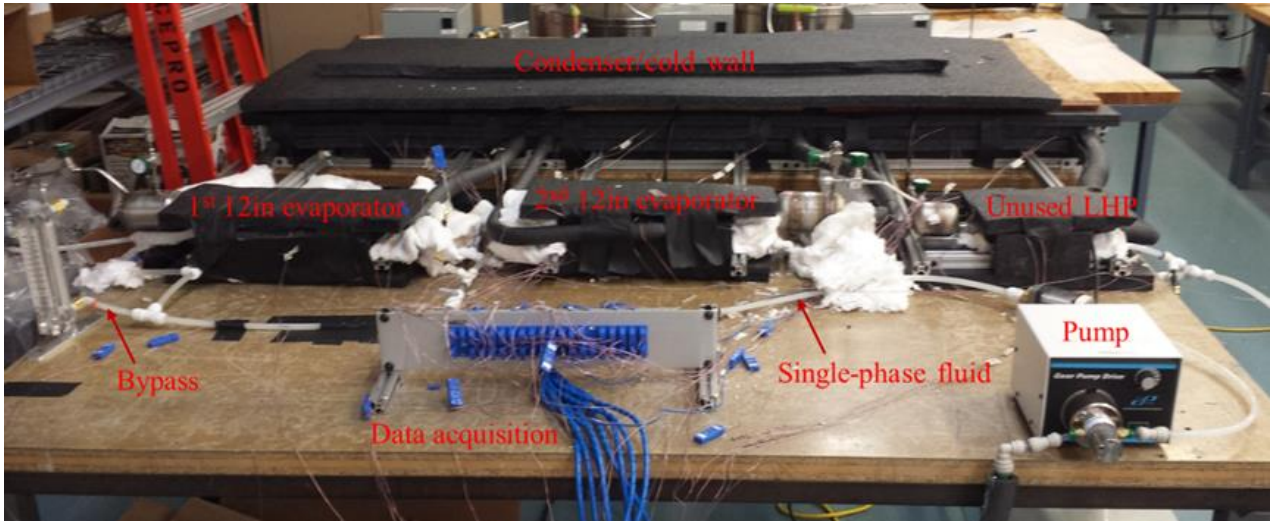
Variable power into *constant sink temperature*



Temperature distribution along the local portion of the SPL as power changes for a sink temperature of -269°C

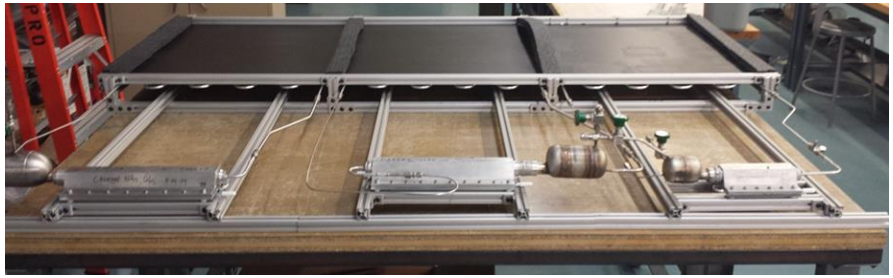
Experimental Validation

- An experimental study was also performed to demonstrate the feasibility of the concept
- An experimental setup was constructed using existing LHPs from previous development programs at ACT
  - Test setup originally designed for 3 LHPs in series, but third LHP would not start up
  - 2 remaining LHPs: flanged evaporator coupled to pumped water loop through heat spreader plates
  - Pumped water loop configured with bypass loop to vary local water flow rate
- Due to large number of complex variables that are involved in the Thermal Desktop modeling, a direct comparison between the test setup and the model was not made
- However, a scaled down proof-of-concept system can clearly demonstrate the general conclusions of the modeling results

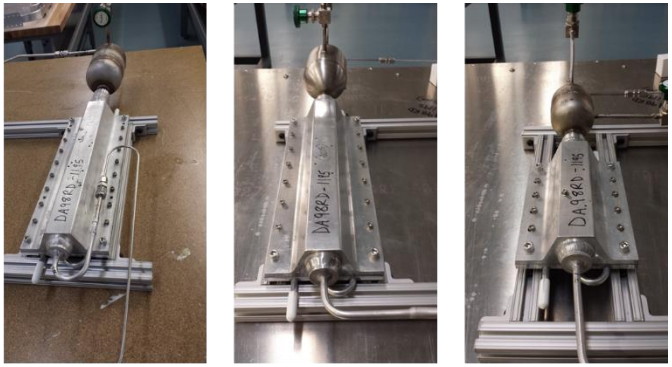


Experimental test setup

Variable Heat Rejection Multiple LHP test setup



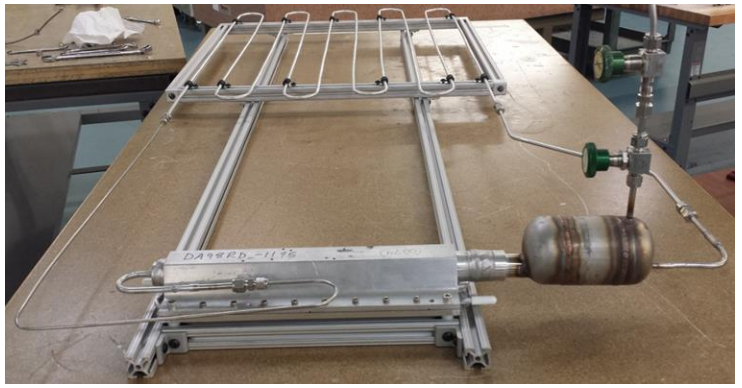
3 LHPs sharing common condenser



First 12in evaporator Second 12in evaporator 6in evaporator

LHP evaporators used in test setup

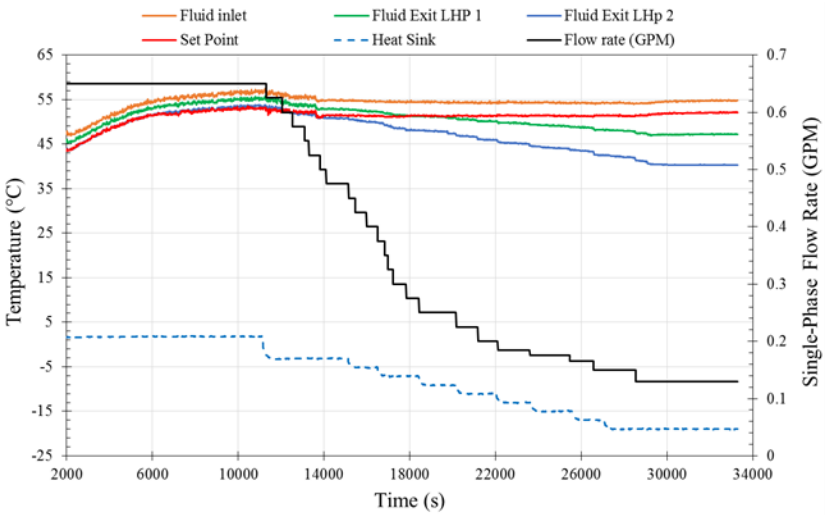
Fully assembled and insulated test setup

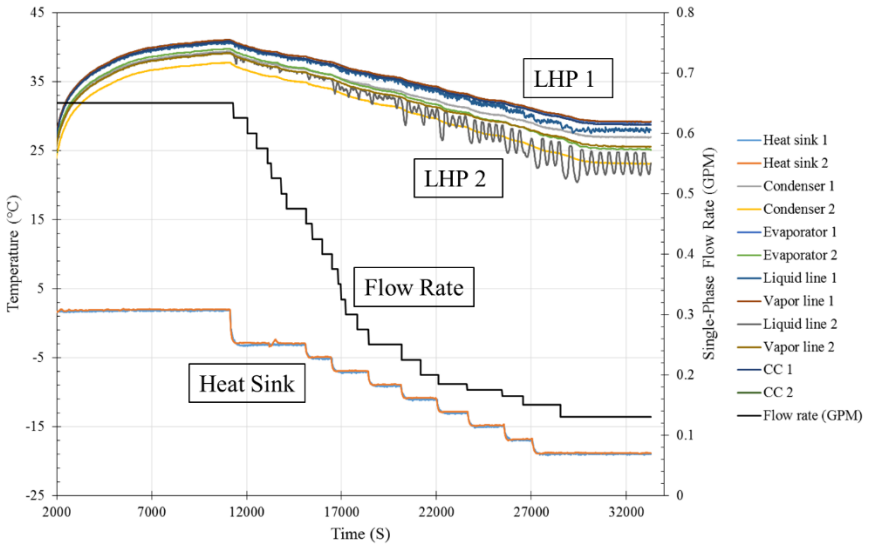


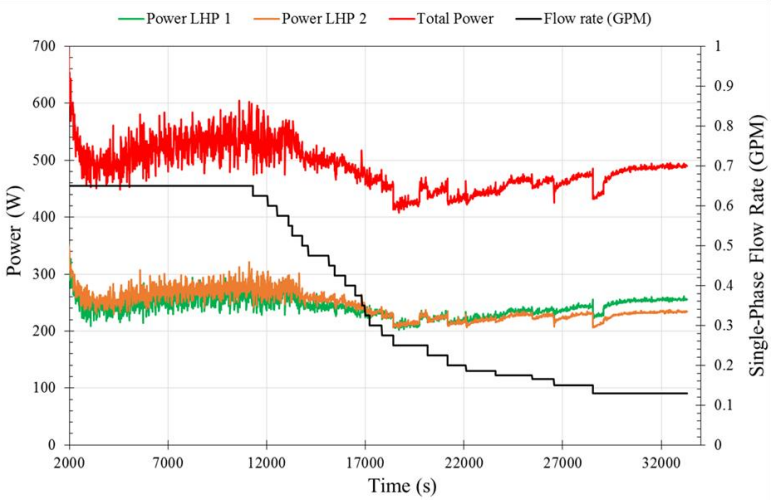
Reassembled LHP using existing pump

Experimental results

- First test – variable heat sink, constant heat load
  - As heat sink temperature dropped form 2°C to -19°C, set point temperature held to within 1°C
  - Heat rejected by LHPs was fairly constant around 400-500 W
  - LHP control only through flow rate variation

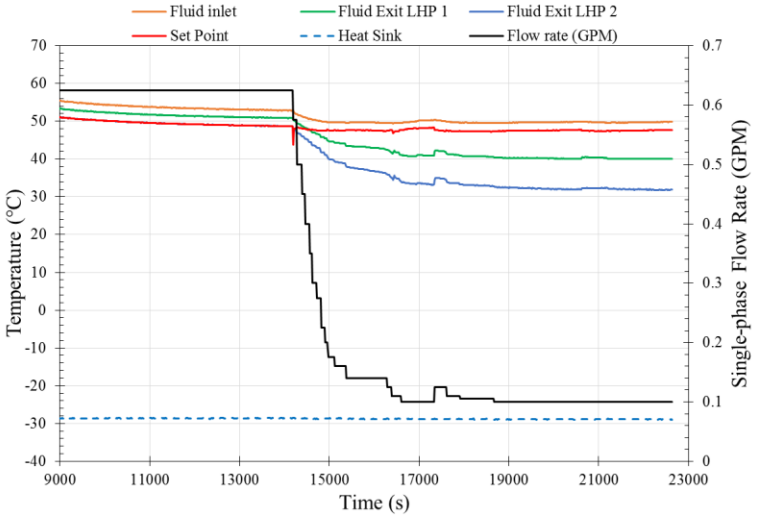


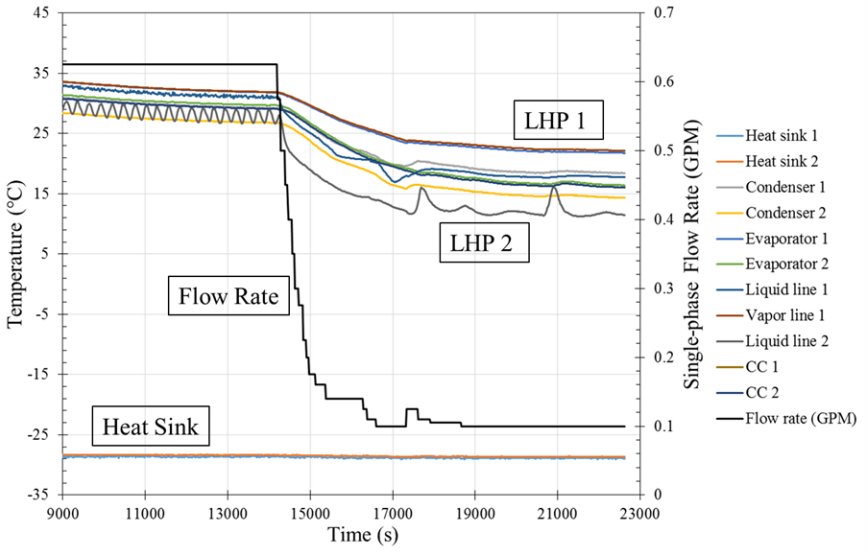


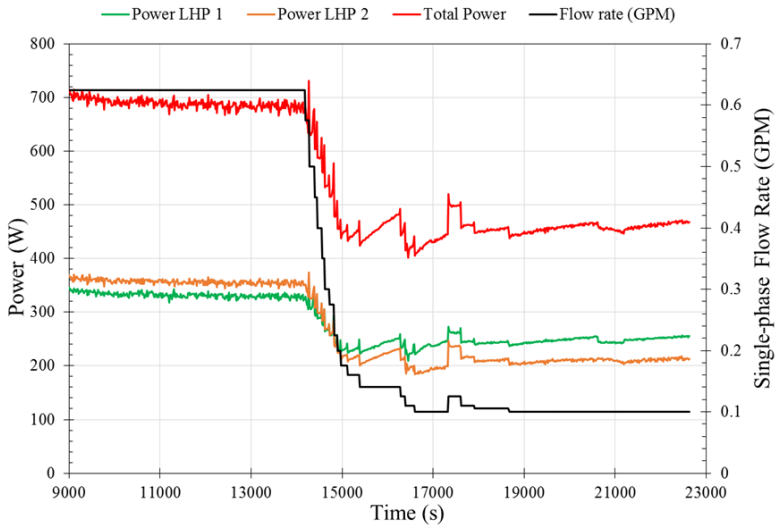


Experimental results

- Second test – variable heat load, constant heat sink
  - For a constant heat sink temperature of -29°C, the heat load was reduced from 700 W to 450 W – turndown of 1.5:1
  - As power was reduced, outlet set point temperature was held within 0.5°C
  - LHP control only through flow rate variation







Conclusions

- Developed a novel method of control for a multiple-LHP system through the modulation of the local flow rate of the single-phase pumped fluid, while maintaining constant total flow rate
- Modeling effort demonstrated capability of maintaining single-phase fluid set point as sink temperature varies from -41°C to -269°C while rejecting 2.5 kW
- Modeling effort also demonstrated a turndown ratio of **10:1** for a 2.5 kW, 3 LHP system at sink temperatures of -41°C and a turndown ratio of 1.5:1 for the same system at sink temperatures of -269°C
- Flow rate based control was demonstrated experimentally with a 2 LHP system for both cases, validating the numerical results
  - Varying sink, constant heat load – maintained set point as sink temperature dropped 20°C
  - Varying heat load, constant sink – demonstrated turndown ratio of 1.5:1

Questions?

Acknowledgments

This work was supported by NASA under contract No. NNX14CJ24P
NASA Technical Monitor was Eugene Ungar
Technician Support provided by Brent Bennyhoff and Larry Waltman